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*Research article*

## Speed control of synchronous machine by changing duty cycle of DC/DC buck converter

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**Abstract:** Renewable energies such as wind or solar energy are naturally intermittent and can create technical challenges to interconnected grid in particular with high integration amounts. In addition, if wind or solar is used to supply power to a stand-alone system, continuous power supply will be met only if sufficient energy storage system is available. The global penetration of renewable energy in power systems is increasing rapidly especially wind and solar photovoltaic (PV) systems. Hybrid wind and solar PV generation system becomes very attractive solution in particular for stand-alone applications. It can provide better reliability since the weakness of one system could be complemented by the strength of the other one. When wind energy is integrated into grid, maximum power point tracking control could be used to optimize the output of wind turbine. In variable speed wind turbine, the turbine speed is varied according to the wind speed. This paper presents a comparison between two methods of controlling the speed of a wind turbine in a microgrid namely; Proportional-Integral (PI) control of the tip speed ratio and stored power curve. The PI method provides more controllability, but it requires an anemometer to measure the wind speed. The stored power curve method, however, is easier to implement, but the amount of energy extracted can be less. The system has been modelled using Matlab/Simulink.

**Keywords:** wind energy; wind turbine; tip speed ratio; stored power curve; buck converter

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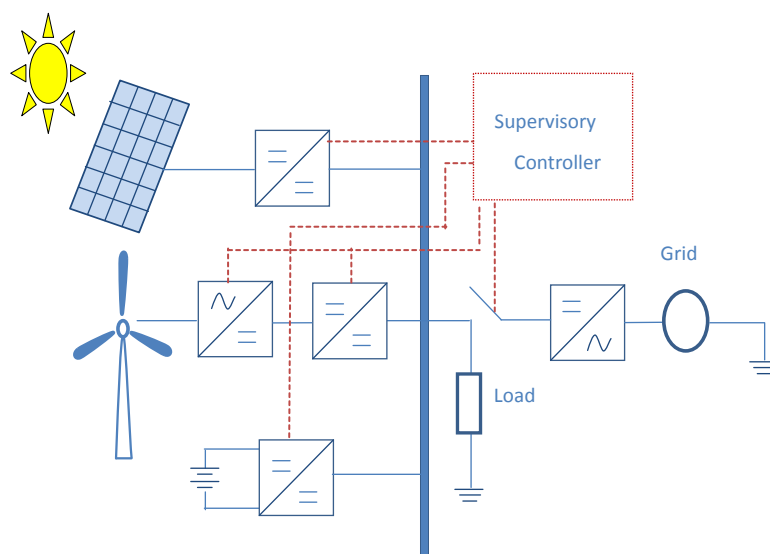
## 1. Introduction

Solar Photovoltaic (PV) and wind energies are intermittent and unpredictable in nature. Therefore, proper scheduling and forecasting tools are required to improve system reliability. Furthermore, combining the two technologies together can improve the availability of the overall system because one energy source can complement the other. During sunny and windy days/hours, power is generated from solar PV and wind turbines. Energy storage systems such as batteries can play a great role in supporting power supply as they can act as balancing devices that provide power (discharging) when there is an energy deficiency and store excess energy (charging) when there is surplus power from renewable energy sources. Hence, hybrid solar PV and wind power system along with batteries can minimize the effect of intermittency and provide continuous power to the load and/or grid. This hybrid system becomes a good solution for power when the infrastructure facilities such as overhead lines, gas lines, etc. are far away from loads or they are expensive and/or difficult to construct. This also has become a very attractive solution for stand-alone systems.

Figure 1 shows a hybrid solar PV and wind system along with battery bank. The common DC bus is connected to the grid via a DC/AC converter. The system can work in either grid-connected mode or stand-alone mode. The DC output voltages from individual solar PV and wind stream, through individual DC/DC and AC/DC-DC/DC units, are integrated and combined in parallel to provide power to the grid/load even with only one source available without the need to work with constant frequency. The different generating sources are not required to be synchronized with the grid which will simplify the operation of the overall system in particular when changing from one mode of operation to the other. The common DC bus voltage is set to be fixed and the output current from each source is controlled independently through individual converters.

In grid-connected mode of operation, the renewable energy sources act as current sources that inject power directly into the DC bus. The battery bank interfaced by a bi-directional converter and can be charged or discharged depending on the situation of the generation, load and its state of charge. The common DC/AC inverter regulates the DC voltage by injecting/absorbing power to/from the grid. In stand-alone mode of operation, the renewable energy sources still act as current sources feeding directly the load while the battery converter regulates the DC bus by charging (in case of extra power) or discharging the battery (in case of shortage of power). Hence, the battery system acts as a voltage source. In grid-connected mode, the output power from individual renewable energy sources is extracted using a maximum power point tracking (MPPT) technique. The same thing is applicable in the stand-alone mode provided that the battery bank exists as a voltage source to control the DC bus voltage by charging or discharging depending on the status of generation and load requirement.

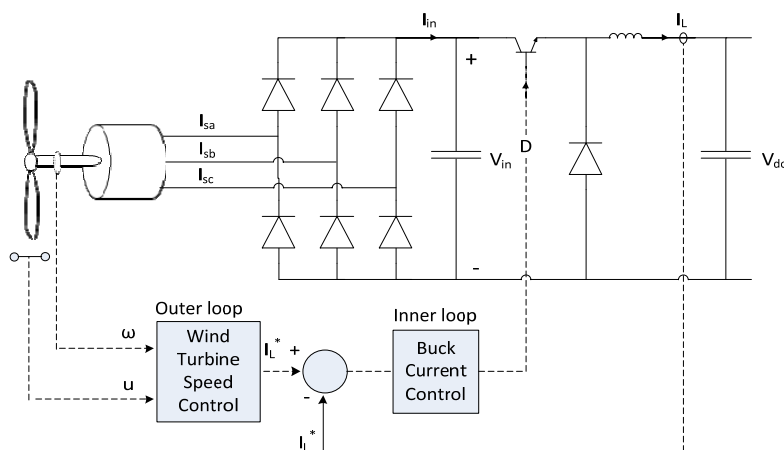
Various papers have been reported and published for control of wind power system or hybrid wind and solar photovoltaic (PV) power systems [1–8]. This paper focuses on the modelling and control design of the wind energy systems. The paper presents a comparison between two methods of controlling a wind turbine in a microgrid namely, PI control of the tip speed ratio and stored power curve. The paper will provide brief information about the wind energy system along with modelling and the two methods of speed control. Simulation results from simplified and detailed models will be presented.



**Figure 1. Hybrid system with AC microgrid.**

## 2. Materials and Method

The wind energy system that is considered in this paper is shown in Figure 2. It consists of a wind turbine, a permanent magnet synchronous machine (PMSM), a rectifier and a DC/DC buck converter. The power output is controlled by regulating the buck output current  $I_L$  injected into the common DC bus. The controller system consists of two loops. The inner loop controls the buck inductor current by varying the duty ratio of the buck power switch. The outer loop controls the speed of the wind turbine by varying the current demand  $I_L^*$  of the inner loop.



**Figure 2. Wind energy system.**

## 2.1. Wind turbine modelling

The wind turbine output mechanical power can be expressed by the following equation:

$$P_m = \frac{1}{2} \rho \pi R^2 u^3 C_p \quad (1)$$

where

$P_m$  : turbine mechanical power

$\rho$  : air density

$R$  : turbine rotor radius

$u$  : wind speed

$C_p$  : turbine performance coefficient (rotor efficiency)

The performance coefficient  $C_p$  is a function of the tip speed ratio  $\lambda$  and the pitch angle  $\beta$  in a pitch controlled system. The wind turbine considered in this paper has a fixed blade pitch angle. The tip speed ratio (TSR) is given by the following equation:

$$\lambda = \frac{R\omega}{u} \quad (2)$$

where  $\omega$  is the turbine rotational speed. The relationship between  $C_p$  and  $\lambda$  is non-linear. For the turbine considered in this paper, this relationship is shown in Figure 3. This curve has been produced experimentally by testing the wind turbine under variable wind speed. It can be noticed that the maximum output power for the considered turbine is obtained when  $\lambda = 1.3$ . The turbine rotational speed is given by:

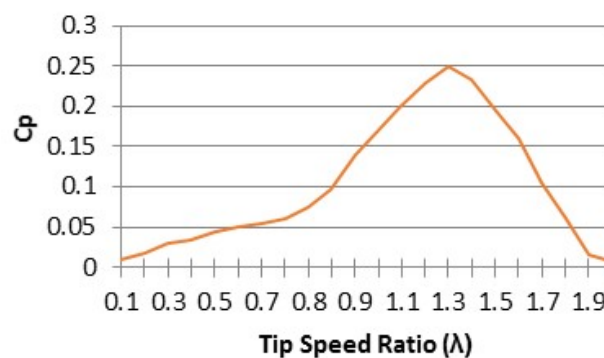
$$\omega = \frac{1}{J} \int (T_m - T_e) dt \quad (3)$$

where

$T_m$ : turbine mechanical torque

$T_e$ : turbine electrical torque

$J$ : rotational inertia



**Figure 3. Power coefficient curve.**

The mechanical output torque depends on the turbine output mechanical power and turbine rotational speed. It can be calculated as follows:

$$T_m = \frac{P_m}{\omega} \quad (4)$$

where  $P_m$  is the turbine mechanical power and  $\omega$  is the turbine rotational speed. The electrical torque is related to the PMSM stator current  $I_s$  by

$$T_e = K_I I_s \quad (5)$$

where  $K_I$  is the machine torque constant. In this system, the electrical torque is controlled by controlling the buck output current  $I_L$  rather than the machine stator current  $I_s$ . Hence, the electrical torque can be related to the buck current via a new defined constant  $K_T$

$$T_e = K_T I_L \quad (6)$$

Equations (1) to (6) represent the model for the wind turbine system and combined together to form the block diagram model shown in Figure 4.

## 2.2. Speed control of wind turbine

Two methods for controlling the speed of the wind turbine have been considered namely; stored power curve and PI control of the  $\lambda$ . Both methods are described below:

### a) Stored Power curve

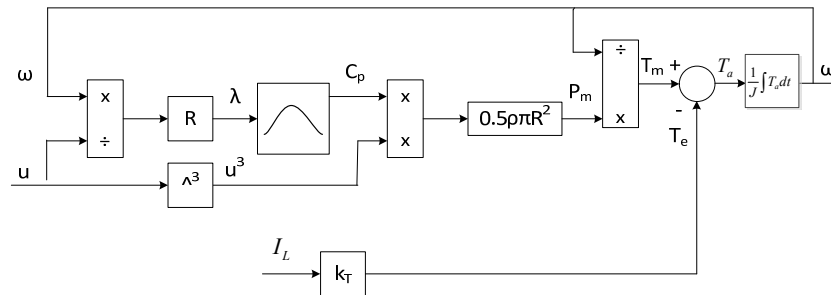
The relationship between  $C_p$  and  $\lambda$  is a non-linear curve shown in Figure 3. The maximum output power of the wind turbine considered in this paper is obtained when  $\lambda = 1.3$  which corresponds to  $C_p = 0.25$ . In order to extract maximum possible power at a given wind speed condition, the wind turbine speed needs to vary so the tip speed ratio  $\lambda$  is always 1.3. Substituting (2) in (1) and using the above values for  $C_p$  and  $\lambda$  gives the maximum power

$$P_{max} = \frac{1}{2} \rho \pi R^2 \left( \frac{R * \omega}{1.3} \right)^3 0.25 \quad (7)$$

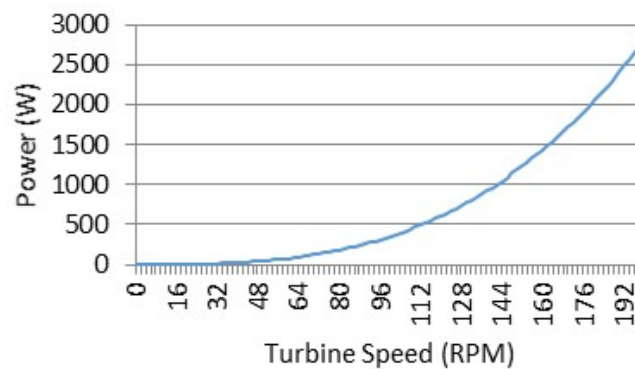
Equation (7) defines the relationship between maximum power that can be extracted versus turbine speed. The optimised stored power curve has been plotted for turbine speed varying from 0 to 200 RPM as shown in Figure 5. This curve can be used to control the speed of the wind turbine without the need to measure the wind speed. That can be done by creating a lookup table that produces a particular power demand for a particular turbine speed. This controller is as shown in Figure 6.

### b) PI Control of the $\lambda$

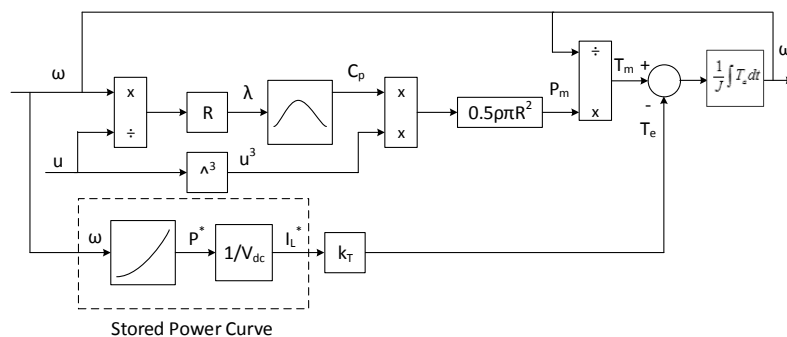
The second control method considered in this paper is PI method. This method is shown in Figure 7. The turbine speed and the wind speed are measured and  $\lambda$  is calculated using (2). The calculated  $\lambda$  is then compared with the optimal  $\lambda^*$  which is 1.3 in this case. The error signal is fed into a PI controller that sets the current demand for the inner loop controller of the buck current.



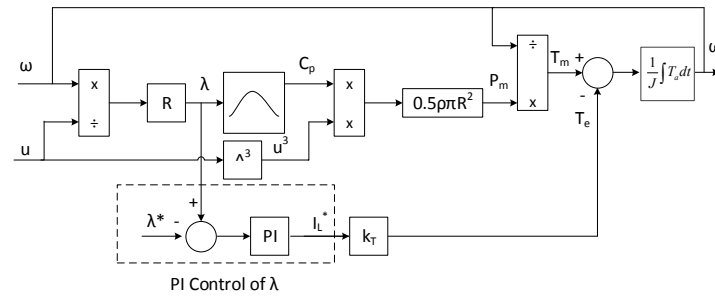
**Figure 4. Block diagram of the system model.**



**Figure 5. Stored power curve.**



**Figure 6. Stored power curve control.**



**Figure 7. PI control of  $\lambda$ .**

### 3. Results and Discussion

#### 3.1. Simulation results of the simplified model

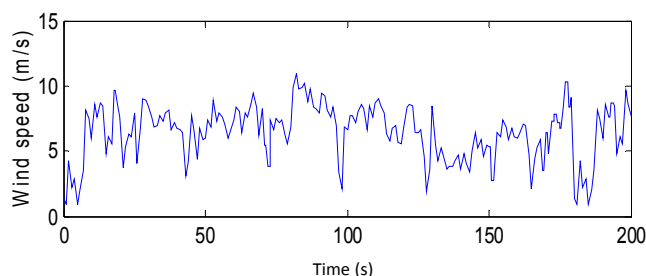
Figures 6 and 7 use a simplified model of the system in which the buck demand current  $I_L^*$  (the output from the stored power curve and PI controllers) is directly proportional to the electrical torque  $T_e$ . In this simplified model, the electric system including the PMSM, the rectifier, the DC/DC buck converter are all linearized and represented by the torque coefficient  $K_t$ . The two models represented in Figures 6 and 7 were built in Matlab/Simulink. Weather data were measured on the roof of the Environmental Sustainable Institute (ESI) in the University of Exeter-Penryn Campus. The measurements were taken using MetPak Pro (Gill Instruments). It is a multi-sensor instrument that can be used to measure essential weather data such as wind speed, wind direction, temperature, pressure, humidity, etc. Wind speed is measured every second at ESI and a sample of measurement for 07/04/2014 is shown in Figure 8. It was used as an input to the wind turbine model. Table 1 below shows the system parameters used in the simulation.

**Table 1. Values used in the simplified model simulations.**

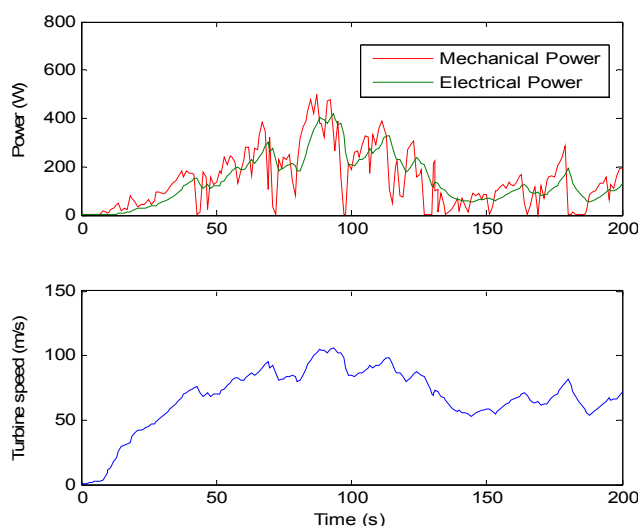
Symbol	Description	Value
$J$	Rotational inertia	38 kg.m <sup>2</sup>
$R$	Turbine rotor radius	1m
$V_{dc}$	DC voltage source in buck converter	50V
$P_{c1}$	Wind speed controller - Proportional Parameter (for results in Figure 10 below)	15
$I_{c1}$	Wind speed controller - Integral Parameter (for results in Figure 10 below)	2.5
$P_{c2}$	Wind speed controller - Proportional Parameter (for results in Figure 11 below)	130
$I_{c2}$	Wind speed controller - Integral Parameter (for results in Figure 11 below)	0

Figure 9 shows the electrical and mechanical powers along with wind turbine speed for the stored power curve control method. As can be seen, the electrical power curve is having a smooth

follow up of the mechanical power curve in corresponding to changes in wind speed. The generated electrical energy was 28.81 kJ. The stored power curve control method is very simple and straightforward way of control of power with no complication at all.



**Figure 8. Measured wind speed at ESI.**

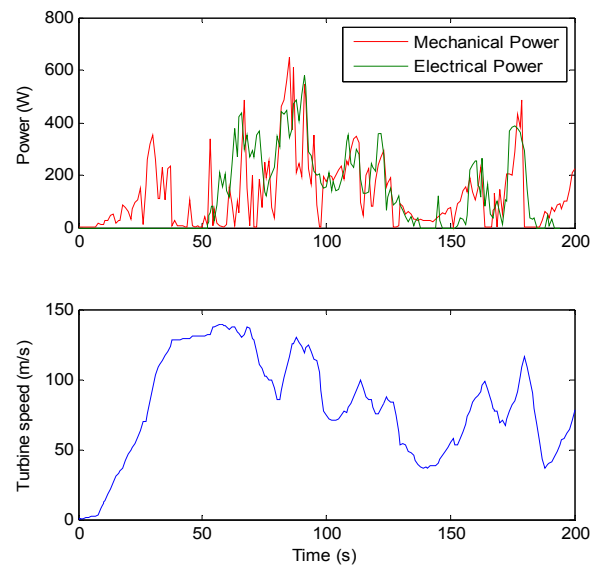


**Figure 9. Power & speed for stored power curve case.**

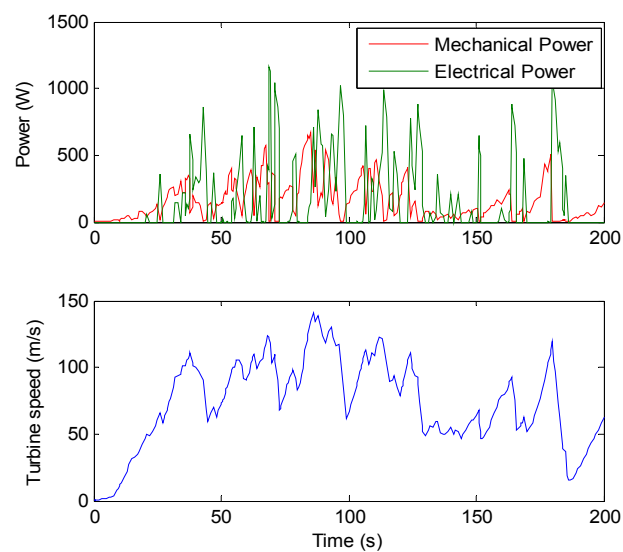
For the PI control method, the Simulink PI control block was used and the values of the controller parameters; Proportional (P) and Integral (I) were changed to have different electrical power and torque responses. In other words, by changing those parameters, different values of electrical power and torque can be obtained. The PI method provides more controllability in comparison to the stored power curve control method, but it requires an anemometer to measure the wind speed. Figure 10 shows the electrical and mechanical powers along with wind turbine speed for the PI control method with PI parameters values of  $P_{c1}$  and  $I_{c1}$  as shown in Table 1. By changing the parameters to the values of  $P_{c2}$  and  $I_{c2}$  of Table 1, the maximum generated electrical energy was obtained. It was equal to 30.39 kJ for the PI control method against 28.81 kJ for the stored power curve control. However, the maximum generated electrical energy in the case of PI control of  $\lambda$  was obtained at the expenses of



more fluctuations in the generated power and turbine speed as can be seen in Figure 11. The turbine speed is changing a lot which is not good for the machine.



**Figure 10. Power & speed for PI control of  $\lambda$  case.**



**Figure 11. Maximum power & speed for PI control of  $\lambda$  case.**

### 3.2. Simulation results of the detailed model

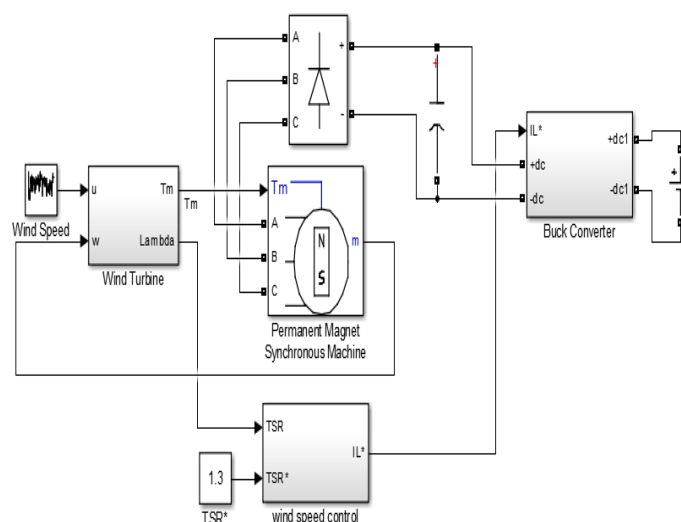
A detailed model of the system was built in Matlab/Simulink using SimPowerSystem toolbox as shown in Figure 12. The wind turbine block includes equations (1) and (2). The mechanical torque is fed into the PMSM. The three-phase output of the PMSM is connected to a passive rectifier. The PI control method is used. The rectified voltage is connected to a DC/DC buck converter. The measured

$\lambda$  (TSR) value by equation (2) in the wind turbine block is fed to the wind speed control block and then compared with the optimal  $\lambda^*$  (TSR\*), which is 1.3 in this case. The error signal is fed into a PI controller, with  $P_{c3}$  and  $I_{c3}$  values as shown in Table 2, which sets the current demand for the buck converter. The simulation parameters used are shown in Table 2. The same wind speed data shown in Figure 8 is used.

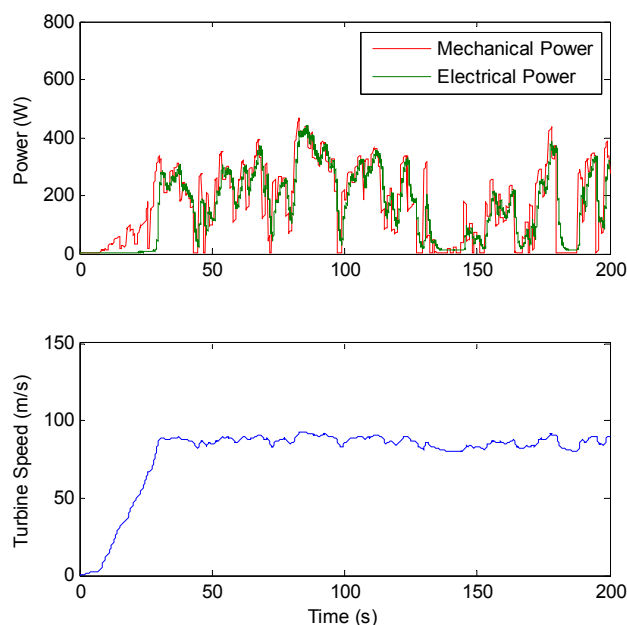
**Table 2. Values used in the detailed model simulations.**

Symbol	Description	Value
$J$	Rotational inertia	38 kg.m <sup>2</sup>
$R$	Turbine rotor radius	1m
$R_s$	Machine stator phase resistance	0.425 $\Omega$
$L_a$	Machine armature inductance	0.000835 H
$K_t$	Machine torque constant	5.308
$P$	Machine pole pairs	5
$V_{dc}$	DC voltage source in buck converter	50V
$L$	Inductor in buck converter	500 $\mu$ H
$C$	Capacitor in buck converter	300 $\mu$ F
$P_{c3}$	Wind speed controller - Proportional Parameter	15
$I_{c3}$	Wind speed controller - Integral Parameter	2.5

Electrical power, mechanical power and turbine speed results are shown in Figure 13. The generated electrical energy is 32.05 kJ. It is slightly higher than the obtained values with simplified models in both speed control types (stored power curve and PI control of the  $\lambda$ ) and the result looks better where the electrical power curve is almost following the mechanical power curve. The turbine's speed has very little fluctuations and almost constant once it reached its peak value.



**Figure 12. Detailed model.**



**Figure 13. Power & speed for detailed model.**

#### 4. Conclusion

The paper presents a comparison between two methods of controlling the speed of a wind turbine in a microgrid namely; PI control of the tip speed ratio and stored power curve. The PI method provides more controllability, but it requires an anemometer to measure the wind speed. The stored energy method, however, is easier to implement, but the amount of energy extracted can be less.

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#### Conflict of Interest

All authors declare no conflicts of interest in this paper.

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